Research Paper | Education | E-ISSN No : 2454-9916 | Volume : 10 | Issue : 9 | September 2024

HOW CAN THE CHOICE OF MATERIALS IMPROVE THE STRENGTH-TO-WEIGHT RATIO AND SUSTAINABILITY IN AEROSPACE APPLICATIONS?

Bradley Hawana

ABSTRACT

This systematised literature review explores current materials that optimise both strength-to-weight ratio and sustainability in aerospace applications, a critical challenge to reducing the industry's environmental impact while maintaining high-performance standards. The review focuses on the properties and applications of Carbon Fibre-Reinforced Polymers (CFRPs), Glass Fibre-Reinforced Polymers (GFRPs), and Aluminium Alloys (AAs). Through a detailed review of these materials, the paper evaluates their ability to address the issues of both high performance through strength-to-weight ratios and sustainability through recyclability and reusability. The findings highlight that CFRPs offer superior strength-to-weight ratios but face sustainability challenges due to recycling difficulties. GFRPs, while less strong, provide a more cost-effective and recyclable option suitable for secondary structures. Aluminum Alloys, particularly the 2XXX and 7XXX series, offer high performance and recyclability with some drawbacks, making them a viable choice for various aerospace components. This study addresses the need to understand which materials provide high strength while maintaining low weight in aerospace applications; simultaneously, there is a pressing need to address sustainability through recyclability and reusability in the aerospace industry.

KEYWORDS: Strength-to-Weight, Sustainability, Fibre-Reinforced Polymers, Aluminium Alloys, Aerospace

1. INTRODUCTION

The aerospace industry faces the critical challenge of enhancing aircraft performance and efficiency while addressing environmental sustainability. Achieving an optimal balance between strength and weight in materials is crucial for improving fuel efficiency, reducing emissions, and increasing the overall operational efficiency of aircraft and other aerospace applications. However, this must be accomplished without compromising the structures' safety, reliability, and durability--as clearly needed by aircraft manufacturing standards (Bristow et al., 2007). The increasing demand for sustainable solutions adds another layer of complexity, as materials must excel in performance and minimise environmental impact through recyclability and reusability. Extensive research has been conducted on the properties and applications of various materials used in the aerospace industry, such as CFRPs, GFRPs, and different alloys like aluminium alloys (Vermeulen et al., 2006). These materials are known for their high-performance characteristics. There is also ample research on their recyclability and reusability. This review explores how advanced materials can address these factors to solve the multifaceted problem of strength while maintaining sustainability.

For several reasons, the aerospace industry must find an optimal balance between strength-to-weight ratio and sustainability. Materials with superior strength-to-weight ratios enhance fuel efficiency by reducing the aircraft's overall weight, leading to lower fuel consumption and cost (Zhu et al., 2018). Higher strength-to-weight also improves performance metrics, structural integrity, and safety (Singh et al., 2017). As one of the most carbon-intensive industries, sustainability in material choice is becoming increasingly important as the industry aims to reduce its environmental footprint (Eckelman et al., 2014; Howe et al., 2013). Using more recyclable and reusable materials can significantly lower the lifecycle environmental impact of aerospace components, aligning with global sustainability goals and regulatory requirements (Eckelman et al., 2014). Thus, prioritising these factors is crucial for the future development and success of the aerospace industry.

Despite the considerable research on aerospace materials, significant gaps remain in understanding how to optimise the strength-to-weight ratio and sustainability. Existing studies often focus on either performance metrics or environmental impacts in isolation without a comprehensive approach that integrates both aspects. Furthermore, there is limited research on the long-term effects of using sustainable materials in high-performance aerospace applications, including their durability, lifecycle impacts, economic feasibility, and potential trade-offs. Addressing these gaps requires an analysis of different materials, considering their mechanical properties and environmental sustainability.

This paper will address the problem of simultaneously tackling strength and sustainability through a systematised review of the characteristics and applications of various aerospace materials. Specifically, this paper will focus on fibre-reinforced polymers such as CFRPs and GFRPs and metal alloys such as aluminium alloys. The analysis will explore how these materials can meet stringent performance metrics while considering sustainability factors such as recyclability, reusability, and environmental impact. The review will address the dual challenge of enhancing performance and ensuring sustainability, which is

vital for advancing the aerospace industry, through examples of high-performance applications in the aerospace industry, demonstrating the critical importance of material choice in these contexts, and provide insights into optimising material selection for future aerospace developments by investigating the interplay between strength-to-weight ratios and sustainability.

2. BACKGROUND

In the aerospace industry, materials like metal alloys and composites are used to meet rigorous high-performance requirements and ensure safety, performance, and efficiency (M'Saoubi et al., 2015). High-performance materials in aerospace are characterised by their exceptional specific strength and stiffness while maintaining low weight. These technical parameters are crucial as they directly influence the aircraft's performance in terms of manoeuvrability, fuel efficiency, and safety (Asyraf et al., 2022; Hegde et al., 2019; Joshi et al., 2016). The strength-to-weight ratio, a critical parameter for aerospace materials, is measured by dividing a material's ultimate tensile strength by density. This ratio indicates how much load a material can bear relative to its weight, impacting the overall efficiency and performance of the aircraft (Hegde et al., 2019; Joshi et al., 2016). High strength-to-weight ratios allow lighter structures to carry more payload or achieve greater fuel efficiency (Joshi et al., 2016; Hegde et al., 2019). This measurement is essential for material selection, guiding engineers in designing components that meet stringent aerospace standards while minimising weight (Hegde et al., 2019). The importance of these parameters cannot be overstated, as they significantly impact aircraft performance (Singh et al., 2017).

In the aerospace industry, the most notable aspects of sustainability encompass reusability and recyclability, which are crucial for reducing the industry's environmental impact. Recyclability involves recovering and reprocessing materials to create new products, particularly critical for managing end-of-life aircraft components (Joshi et al., 2016). Reusability involves reincorporating and reusing components, reducing waste and extending their lifecycle (Joshi et al., 2016). Recovering and reprocessing these materials to create new components is essential to conserve resources and minimise waste (Joshi et al., 2016). Developing efficient recycling and reusing processes for aerospace materials is crucial in addressing the aerospace industry's increasing carbon footprint (Asyraf et al., 2022; Joshi et al., 2016).

3. METHODOLOGY

Objective: The primary objective of this systematised review is to evaluate the performance and sustainability of various materials used in aerospace applications. The review aims to answer the following key questions: What are the current advancements in materials used for aerospace applications? How do these materials compare in terms of their strength-to-weight ratios? What are the sustainability implications of these materials?

A systematised review is a rigorous method of reviewing and synthesising existing research to answer specific questions within a field of study (Nightingale, 2009). A systematised review was chosen to ensure a comprehensive and unbiased literature synthesis. Unlike traditional literature reviews, which may be more narrative, systematised reviews follow a structured approach to ensure comprehensiveness and reproducibility (Nightingale, 2009). The systematised review process involves several key steps, each designed to ensure a comprehensive and unbiased literature synthesis. The formulation of research questions guided the review process, ensuring that the search and analysis were focused and relevant. A detailed search strategy was developed, including specific databases, search terms, and inclusion/exclusion criteria.

Identifying and collecting relevant sources of information was achieved by comprehensively searching technical papers, material databases, and other relevant literature. The data sources included technical papers, material databases, and Ashby charts. Google Scholar was used to search for technical papers. Examples of keywords and search terms included "aerospace materials," "strength-to-weight ratio," "sustainable composites," and "aerospace applications." Specific databases such as Granta Design provided detailed material properties and performance information.

This methodology employed specific design and procedures, including establishing clear selection and evaluation criteria and detailed data extraction protocols to ensure a systematic and rigorous review process. These included selection criteria such as relevance to aerospace applications, focus on strength-to-weight ratios, sustainability considerations, and use of advanced materials. Evaluation criteria included strength-to-weight ratios, durability and performance under extreme conditions, environmental impact and sustainability, and cost-effectiveness. Detailed information on material properties was extracted and compared from each source.

Studies were selected based on relevance and quality, and inclusion and exclusion criteria were applied to select the most appropriate studies. Materials were selected based on their relevance to aerospace applications and industry. The evaluation criteria focused on key performance metrics, including strength-to-weight ratios and sustainability. Furthermore, relevant data were systematically extracted from each selected study and organised to facilitate synthesis and analysis. Findings from different studies were brought together to provide a comprehensive overview, and comparative analysis using Ashby diagrams helped visualise the performance of different materials.

The synthesis of information was a critical step in the review process, which involved integrating findings from multiple sources to form a cohesive and comprehensive understanding of the subject. Each source was evaluated for relevance and quality, and the common themes and trends were synthesised from the information. Sources were analysed by comparing and contrasting findings from different studies, highlighting areas of agreement and divergence, and drawing connections between findings to build a cohesive argument. This approach allowed for a better understanding of the topic and helped build

the argument for the literature review.

4. RESULTS

4.1 Fibre-Reinforced Polymers

Simply, fibre-reinforced polymers (FRPs) are composite materials made of a polymer reinforced with fibres. These fibres can be composed of materials such as glass, carbon, aramid (i.e., aromatic polyamides having at least 85% of their amide linkage attached directly to two aromatic rings; Masuelli et al., 2013), or natural substances (e.g., flax, jute, and epoxy; Nwankwo et al., 2023). The polymer matrix protects the fibres, provides shape, and distributes loads among the fibres, enhancing the material's mechanical properties, such as strength, stiffness, and durability (Masuelli et al., 2013).

The development of Fibre-reinforced polymers began in the early 20th century. The first significant use of FRPs occurred primarily in military applications in the 1940s, where glass fibre-reinforced polymers (GFRPs) became popular due to their favourable strength-to-weight ratio (Tong et al., 2002). The subsequent decades saw advancements in fibre technology and polymer chemistry, resulting in the introduction of advanced fibres like carbon and aramid, which further expanded the applications of FRPs due to their superior mechanical properties. Carbon fibre-reinforced polymers (CFRPs) gained prominence in the 1960s and 1970s, particularly in aerospace and high-performance sporting goods (Tong et al., 2002). The continuous development of FRPs has led to the creation of hybrid composites and nanocomposites, offering enhanced properties and new applications (Asyraf et al., 2022; Boyer et al., 2015).

Fibre-reinforced polymers are known for their high specific strength/strength-to-weight (Joshi et al., 2016; Muhammad et al., 2021; Nagaraju et al., 2023; Zhang et al., 2022), fatigue and corrosion resistance (Asyraf et al., 2022; Joshi et al., 2016; Nagaraju et al., 2023; Zhang et al., 2022), resistance to environmental degradation (Joshi et al., 2016; Muhammad et al., 2021), and lightweight properties compared to traditional materials like metals (Asyraf et al., 2022; Joshi et al., 2016; Muhammad et al., 2021; Zhang et al., 2022). These characteristics make FRPs particularly suitable for applications where high performance is critical, such as in the aerospace, automotive, and construction industries (Joshi et al., 2016). FRPs are also recognised for their unparalleled versatility in tailoring properties by varying the type of fibres and the matrix material. This adaptability makes FRPs suitable for a wide range of applications, including aerospace, automotive, marine, and sports equipment (Asyraf et al., 2022; Joshi et al., 2016; Muhammad et al., 2021; Zhang et al., 2022).

Due to these characteristics, various industries extensively use fibre-reinforced polymers. FRPs are utilised in aircraft structures, interior components, and rotor blades in the aerospace industry due to their lightweight and high-strength properties (Joshi et al., 2016). These applications use Fibre-reinforced polymers (FRPs) due to their high specific strength and stiffness, which allow for lighter and more robust structures compared to traditional materials like metals, essential for structural integrity in aircraft (Asyraf et al., 2022; Masuelli et al., 2013). In aerospace, for instance, reducing weight translates to improved fuel efficiency and performance while reducing emissions (Muhammad et al., 2021; Zhang et al., 2018). Furthermore, FRPs are also known for their ability to customise properties by selecting different fibre and matrix combinations to meet the specific requirements of each application (Masuelli et al., 2013; Zhang et al., 2022).

4.1.1 Carbon Fibre-Reinforced Polymers

Carbon Fibre-Reinforced Polymers (CFRPs) are advanced composite materials with carbon fibres embedded in a polymer matrix (Masuelli et al., 2013). The carbon fibres help provide higher strength and stiffness, while the polymer matrix helps distribute the load and provides structural integrity. CFRPs have stiff and lightweight characteristics (Asyraf et al., 2022), making them suitable for various high-performance applications, particularly in the aerospace industry (Masuelli et al., 2013).

4.1.1.1 Performance

In aerospace applications, the performance requirements are stringent, necessitating strong and stiff materials (Singh et al., 2017). High-performance materials like CFRPs are critical for achieving the necessary performance metrics in aerospace (Asyraf et al., 2022; Tao et al., 2023). The high-performance characteristics of CFRPs are evident in their characteristics and properties. CFRPs offer high specific strength and stiffness (Huda et al., 2013; Nagaraju et al., 2023; Tao et al., 2023; Zhang et al., 2022). Specific strength refers to the strength of a material relative to its density, while stiffness is the ability of a material to resist deformation under stress. For example, standard modulus CFRPs have a strength of around 3450-4830 MPa (Huda et al., 2013; Rajak et al., 2021; Zhang et al., 2018). The specific strength and stiffness of FRPs are between 1.3 and 1.9 g/cm3, compared to 2.7 g/cm3 for aluminium and 7.8 g/cm3 for steel (Muhammad et al., 2021). CFRPs also demonstrate failure strains below 2% without ductility (Asyraf et al., 2022).

Moreover, CFRPs have a high strength-to-weight ratio while maintaining low density (Hegde et al., 2019; Huda et al., 2013; Nagaraju et al., 2023). They are much lighter than metals, while still providing comparable or superior strength. For example, the minimum yield strength of carbon fibre-reinforced polymers (CFRPs) is 550 MPa, while the density of CFRP is only one-fifth that of steel and three-fifths that of Al-based alloys (Zhang et al., 2018). The high strength-to-weight ratio makes using CFRPs effective for commercial transport aircraft, lowering airframe weight and enhancing fuel economy, eventually leading to lower operating costs (Muhammad et al., 2021; Soutis et al., 2005).

CFRPs have allowed for an overall reduction in production and operational costs, where the economy of these parts results in lower production costs and weight savings, subsequently creating fuel savings that lower the cost of operating the plane (Masuelli et al., 2013). For example, in the rudder of a commercial plane, CFRPs boast a 25% reduction in weight and 95% reduction in components by combining parts and

forms into simpler moulded parts compared to a traditional rudder made from sheet aluminium (Masuelli et al., 2013). In all, their application in these aircraft structures enhances performance and significantly reduces weight, fuel efficiency, and operational costs (Huda et al., 2013).

The high specific strength and stiffness with relatively low density make CFRPs a popular material for high-performance applications in the aerospace industry (Tao et al., 2023). Most supersonic aircraft are military aircraft and utilise CFRPs for their main parts (Huda et al., 2013). For example, CFRPs make up nearly one-third of the structure for the Lockheed Martin F-22 Raptor fighter jet (Joshi et al., 2016). They also make up about 40% of the structure for the Eurofighter Typhoon fighter jet. Other European fighter jets, like the Dassault Rafale and Saab Gripen, have between 20-25% CFRP by weight (Muhammad et al., 2021). CFRPs are also used for re-entry nose tips and heat shields in rockets and hypersonic vehicles (Nagaraju et al., 2023).

Because of these high performance characteristics, CFRPs are used extensively in an aircraft's primary and secondary structures, mainly airframe and engine components (Boyer et al., 2015). These elements include fuselage sections, wings, vertical and horizontal stabilisers, and other critical components (Joshi et al., 2016). For instance, in the Boeing 787 Dreamliner, CFRPs make up much of the wing, empennage, and fuselage skins and support structure, significantly reducing the aircraft's weight and improving fuel efficiency (Boyer et al., 2015). The Boeing 787, Boeing 777, and Airbus 350 XWB have up to 50% of their weight in CFRP (Asyraf et al., 2022; Huda et al., 2013; Zhang et al., 2018). Besides Boeing, Airbus also utilised CFRPs in their A310 elevator with a honeycomb core (Muhammad et al., 2021).

4.1.1.2 Sustainability

CFRPs encompass significant aspects of high-performance aerospace applications; therefore, addressing the recyclability and reusability of CFRPs within these applications is critical as sustainability concerns gain prominence. The extensive usage of CFRPs within the aerospace industry has resulted in extensive CFRP waste (Pimenta et al., 2011). Manufacturing waste accounts for almost 40% of all CFRP waste generated (Pickering et al., 2006b; Pimenta et al., 2011), with woven trimmings contributing to 60% of the manufacturing waste (Hunter et al., 2009; Pimenta et al., 2011). This waste usually includes out-of-date pre-pregs (a composite material made from "pre-impregnated" fibres; Pimenta et al., 2011), manufacturing cut-offs (material left over after processing; Pimenta et al., 2011), testing materials, production tools, and End-Of-Life (EOL; meaning the last life cycle stage of a material) components (Pimenta et al., 2011, p. 1). Within 30 years, the almost 8500 new composite-generation commercial aircraft utilising CFRPs for their structural components will be decommissioned, with each aircraft containing more than 20,000 kg of CFRP waste (Pimenta et al., 2011).

Recycling CFRPs is difficult due to their complex compositions of fibre matrixes and fillers, as CFRPs are typically combined with metal fixings, honeycombs, and hybrid composites (Pimenta et al., 2011). Most CFRP waste is landfilled due to CFRP's crosslinked nature of thermoset resins, meaning they cannot be remoulded or recycled (Pimenta et al., 2011). Consequently, the airframe of EoL aircraft are disposed of in these landfills (Pimenta et al., 2011). As CFRPs continue to become more widely used in the aerospace industry, current production raises concerns about proper waste disposal (Pimenta et al., 2011).

By improving the eco-efficiency—that is, an activity-based carbon footprint and direct cost assessment model in manufacturing—of CFRPs, recycling and reusing opportunities exist to improve both the ecological and economic aspects of sustainability in aerospace manufacturing (Al-Lami et al., 2018; Asyraf et al., 2022). The Life Cycle Assessment aims to evaluate and compare the material's life cycle from an environmental perspective, while the Life Cycle Cost Analysis does so from an economic perspective (Al-Lami et al., 2018). From LCA and LCCA assessments carried out in the sense of a representative process model built through the application of Business Process Reengineering (BPR), the carbon footprint of CFRP production is primarily dominated by fibre and energy usage (Al-Lami et al., 2018). The sheer volume of CFRPs currently used in aerospace applications will substantially impact the current and future solid waste generation (Asyraf et al., 2022; Vieira et al., 2017). Therefore, the focus on recycling CFRPs is vital to improving the sustainability of the aerospace industry.

Significant advancements have been made in recycling technologies for CFRPs. One of which is mechanical recycling. Mechanical recycling involves breaking down the CFRPs by shredding, crushing, milling, or other similar mechanical processes to produce smaller scrap pieces (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021; Tao et al., 2023). The recyclates are recovered and segregated by sieving into resign-rich powders and fibres of various lengths (Oliveux et al., 2015; Pimenta et al., 2011). Mechanically recycled carbon fibres are typically reincorporated in new composite materials or used for low-value applications as they do not recover individual fibres (Pimenta et al., 2011; Rani et al., 2021). Mechanical recycling recovers the CFRP's fibres and resin and does not use or produce hazardous material (Pimenta et al., 2011). However, the mechanical performance of the recycled Carbon Fibres (rCFs) recovered from mechanical recycling is significantly degraded, which limits the possibility of rCFs being recycled in this way to be remanufactured (Pimenta et al., 2011; Tao et al., 2023). Recycled fibres recovered from mechanical recycling techniques are not able to maintain their high mechanical properties and fibre integrity, resulting in a decrease in market competitiveness (Pickering et al., 2006a; Pimenta et al., 2011; Tao et al., 2023). Due to the lower value of vGF, mechanical recycling is currently more commonly employed for recycling GFRPs (Karuppannan et al., 2020; Tao et al., 2023).

Chemical recycling is a standard process of fibre reclamation for recycling CFRPs. Chemical recycling consists of decomposing the polymeric resin of CFRPs into large oligomers using a

reactive medium like catalytic solutions, benzyl alcohol, and supercritical fluids (Allred et al., 2001; Jiang et al., 2009; Nakagawa et al., 2009; Pimenta et al., 2011; Tao et al., 2023). In this process, the carbon fibres remain after the process and are extracted (Marsh et al., 2009; Pimenta et al., 2011). Chemical recycling allows the rCFs to retain a significant amount of their mechanical properties and fibre length (Pimenta et al., 2011). However, the process has low contamination tolerance and may pose an environmental hazard from using solvents (Pimenta et al., 2011). Most chemical recycling methods reduce the recycling process's scalability into industrial applications.

Solvolysis is a form of chemical recycling that degrades the CFRP resin by chemically treating it using a solvent (Oliveux et al., 2015). In this process, a reactive solvent diffuses into the composite and breaks specific bonds, allowing carbon fibres to recover from the resin. This process is most widely used for thermoset and thermoplastic resins like CFRPs. Solvolysis can utilise various solvents, temperatures, pressures, and catalysts (Oliveux et al., 2015). Solvolysis uses relatively lower temperatures to degrade the polymers. Because of this, solvolysis can avoid contamination in the fibre's surface, which prevents proper interaction between the rCFs and the new polymer matrix (Oliveux et al., 2015). However, reactors used for solvolysis can be expensive as they have to withstand high pressures and corrosion. Solvolysis has recently become a more popular method to recycle CFRPs (Oliveux et al., 2015). Further research is needed to allow for solvolysis to become more widespread and commercially used (Tao et al., 2023).

Another primary method of recycling CFRPs is fibre reclamation. Fibre reclamation consists of recovering the fibres from CFRPs by breaking down the matrix using thermal or chemical processes (Pimenta et al., 2011). These fibres are released, then collected, and cleaned (Pimenta et al., 2011). rCFs recovered from the fibre reclamation process tend to have a cleaner surface and comparable mechanical properties to previously unused virgin Carbon Fibres (vCFs) and can achieve rCFs with strengths of up to 90% of the vCF (Pimenta et al., 2011; Tao et al., 2023). As CFRPs have high thermal and chemical stability (Pickering et al., 2006b; Pimenta et al., 2011), fibre reclamation processes are most suitable as they do not significantly degrade the mechanical properties of CFRPs (Pimenta et al., 2011). rCFs recycled through fibre reclamation are often re-impregnated with new resin to manufacture recycled CFRPs (rCFRPs) or used in non-structural applications, such as industrial paints, construction materials, electromagnetic shielding, high-performance ceramic brake discs, and fuel cells (Pimenta et al., 2011). Pyrolysis is a widespread recycling process of fibre reclamation for CFRPs, and it involves the thermal decomposition of organic molecules in an inert atmosphere (Oliveux et al., 2015; Pimenta et al., 2011). The process involves heating the CFRP to 450-700°C, which makes the polymeric matrix volatilised into lower-weight molecules while the carbon fibres remain inert and then recovered (Marsh et al., 2008; Meyer et al., 2009; Pimenta et al., 2011). Pyrolysis allows the rCFs to retain most of their mechanical properties without using chemical solvents (Pimenta et al., 2011). However, this process makes some properties of the rCFs sensitive to processing parameters and releases environmentally hazardous off-gases (Pimenta et al., 2011; Tao et al., 2023).

Both solvolysis and pyrolysis are preferred techniques to recycle CFRPs as they both reclaim fibres (Oliveux et al., 2015). These techniques have been proven to recover carbon fibres from CFRPs while maintaining most of their reinforcement capabilities (Oliveux et al., 2015). The mechanical properties of rCFs are determined by the purity of their surface (Oliveux et al., 2015). The rCF's surface's purity affects its ability to adhere to a new material (Oliveux et al., 2015). When reincorporated into new composites, the resin residues left on the surface of the rCF reduce good interaction between the rCF and the new matrix, leading to worse mechanical properties (Oliveux et al., 2015). While rCFs recovered from both processes leave a residual resin at their surface, rCFs recovered from solvolysis are usually cleaner than those recovered by pyrolysis (Oliveux et al., 2015). In contrast, rCFs recovered from pyrolysis leave more evident residual resin that needs to be removed before being reused in new composites (Oliveux et al., 2015). Because of this, solvolysis is more efficient than pyrolysis because of improved mass transfer.

However, current recycling processes of CFRPs do not generate recycled rCFs that can be reused in the same high-performance applications as these techniques cannot preserve the performance and structural characteristics of CFRPs (Oliveux et al., 2015). rCFs usually retain a significant portion of their mechanical properties, though they cannot match those of vCFs. Recycled fibres cannot reach the same performance properties as vCFs as they are unsized, limited in length, and available in random direction distribution (Oliveux et al., 2015). vCFs, on the other hand, are sized and available in multiple lengths (Oliveux et al., 2015). rCFs are also difficult to manipulate, which has limited their reuse potential to applications focusing on down-cycling or reusing unreinforced materials (Oliveux et al., 2015). These fibres can also be used in non-critical aerospace components (Hegde et al., 2019). However, incorporating these rCFs in such materials can lead to higher costs and lower environmental efficiency (Oliveux et al., 2015).

Major challenges still remain in establishing a robust and successful CFRP recycling industry, particularly in addressing technical, economic, and market-related issues (Pimenta et al., 2011). However, adopting rCFRPs represents a crucial step towards sustainable aerospace manufacturing. By leveraging recycled fibres, the aerospace industry can reduce its environmental impact and promote a more sustainable approach to aerospace engineering (Muhammad et al., 2021).

4.1.1.3 Limitations

Despite their advantages, CFRPs are expensive to manufacture and recycle (Geier et al., 2019). CFRP materials cost significantly more because of the complexity of the manufacturing process for carbon fibre, as well as the requirement for more expensive raw materials, with material prices for carbon fibre reaching up to 40£/kg (Muhammad et al., 2021; Oliveux et al., 2015; Pimenta et al., 2011). Different processes such as weaving, non-crimp fabrics, and pre-impregnation of fibres also drive the

cost of CFRP above the purchasing power of the consumers, making it not economically viable in the long run (Al-Lami et al., 2018). The production of CFRP components involves intricate lay-up and curing processes, which require specialised equipment and skilled labour, adding to the overall cost (Al-Lami et al., 2018; Rajak et al., 2021; Witik et al., 2012). Additionally, the machinability of CFRPs poses challenges due to the abrasive nature of carbon fibres, which can cause wear on cutting tools and require specialised machining techniques (Geier et al., 2019; Rajak et al., 2021; Zhang et al., 2018). The need for precise temperature control during curing and the potential for common defects in the final product adds to the complexity of the manufacturing process (Kizaki et al., 2020). The energy consumed during the complex manufacturing process can be up to 165 kWh/kg (Pimenta et al., 2011). The high energy consumption is due to the energy necessary to produce the CFRPs, mainly during the pre-impregnation and autoclave processes (Oliveux et al., 2015). In order to address these cost and manufacturing challenges, further research and development efforts are needed to streamline the CFRP production and recycling process and improve its scalability for commercial applications.

4.1.2 Glass Fibre-Reinforced Polymers

Glass fibre-reinforced polymers (GFRPs) are composite materials that reinforce a polymer matrix with glass fibres. Similar to CFRPs, these fibres increase the composite's strength and stiffness while maintaining a lightweight profile (Morampudi et al., 2021; Nagaraju et al., 2023; Sathishkumar et al., 2014). The glass fibres typically used are made from silica-based glass, woven into mats or formed into rovings, and then impregnated with a polymer resin to form the composite before being hardened (Boyer et al., 2015; Joshi et al., 2016; Kumar et al., 2016). GFRPs are noted to have high stiffness, strength, flexibility, chemical resistance, and insulation while brittle in a polymer matrix, making them tough (Muhammad et al., 2021; Nagaraju et al., 2023; Sathishkumar et al., 2014; Shivanagere et al., 2018; Tao et al., 2023). Additionally, GFRPs are cheaper due to their low fiberising temperature and inexpensive raw materials (Muhammad et al., 2021; Nagaraju et al., 2023). These properties and their low cost make GFRPs more beneficial for a wide range of applications in the aerospace industry (Muhammad et al., 2021).

GFRPs are usually made from two types of glass fibres: E and S glasses (Asyraf et al., 2022; Kumar et al., 2016). E-glass is made up of lime aluminium borosilicate glass with low sodium and potassium levels and has excellent electrical resistance, while S-glass has a higher strength-to-weight ratio (Asyraf et al., 2022; Kumar et al., 2016). S-glass is made with magnesium aluminosilicates and is typically used where high strength, stiffness, extreme temperature resistance, and corrosive resistance are needed, which is why it is primarily used for military and aerospace applications (Kumar et al., 2016; Morampudi et al., 2021; Rajak et al., 2021; Sathishkumar et al., 2014; Tao et al., 2023).

4.1.2.1 Performance

GFRPs meet the performance requirements for specific aerospace applications by providing a favourable balance of mechanical properties and weight (Tao et al., 2023). GFRPs are noted for their high specific strength and stiffness, excellent tensile strength, and durability, which makes them a popular material used extensively across the aerospace industry (Joshi et al., 2016; Morampudi et al., 2021; Rajak et al., 2021; Sathishkumar et al., 2014; Shivanagere et al., 2018; Tao et al., 2023). For instance, GFRPs have a tensile strength ranging from 200-780 MPa depending on the type of glass fibres used (Sathishkumar et al., 2014), with GFRP laminates having an ultimate tensile strength of around 500 MPa (Ferdous et al., 2020; Rajak et al., 2021). S-glass fibres used for GFRPs also have a high tensile strength of around 4480-4890 MPa (Kumar et al., 2016; Sathishkumar et al., 2014). GFRPs are also noted to be flexible while maintaining their strength (Masuelli et al., 2013). For example, S-Glass GFRPs have a high modulus of elasticity (Ferdous et al., 2020), reaching up to 89 GPa (Kumar et al., 2016). The flexural strength and modulus of GFRPs can reach up to 444 MPa and 27075 MPa, respectively, depending on the type of glass fibres used (Sathishkumar et al., 2014). GFRPs are also noted to have the strongest and most resistant to deforming forces when the polymer fibres are parallel to the force exerted (Masuelli et al., 2013).

GFRPs have high strength while maintaining low density and being lightweight, though heavier than CFRPs (Ferdous et al., 2020; Joshi et al., 2016; Kumar et al., 2016; Muhammad et al., 2021; Nagaraju et al., 2023; Rajak et al., 2021; Sathishkumar et al., 2014; Shivanagere et al., 2018; Tao et al., 2023). GFRPs are still much lighter than traditional metals while providing comparable strength. For example, GFRPs have a compressive strength of around 1080-1600 MPa. The density of GFRP laminates is around 2.53 g/cm3, compared to densities ranging between 2.7-7.8 g/cm3 for traditional metals usually found in aircraft (Ferdous et al., 2020; Kumar et al., 2016; Muhammad et al., 2021). GFRPs had greater stiffness than aluminium and had less relative density than steel (Morampudi et al., 2021). Moreover, GFRPs are cheaper due to their low fiberising temperature and inexpensive raw materials (Muhammad et al., 2021; Nagaraju et al., 2023). These properties and their low cost make GFRPs more beneficial for a wide range of applications in the aerospace industry (Muhammad et al., 2021).

While not as strong or stiff as CFRPs, GFRPs offer adequate performance and are an extensively used material in aircraft manufacturing (Joshi et al., 2016; Masuelli et al., 2013; Sathishkumar et al., 2014; Zhang et al., 2022). Because of this, GFRPs are commonly used in secondary structures, interior components, and non-load-bearing parts (Joshi et al., 2016; Masuelli et al., 2013; Zhang et al., 2022) and are not widely used for the construction of primary airframes as there are alternative materials like CFRPs which better suit the applications in the aerospace industry (Sathishkumar et al., 2014). Typical applications of GFRPs include aircraft radomes, fairings, ducting systems, engine cowlings, luggage racks, bulkheads, storage bins, instrument enclosures, and antenna enclosures (Boyer et al., 2015; Sathishkumar et al., 2014). For example, the rotors and other structures in the rotor system of the V-22 (Osprey) tilt-rotor aircraft are made of GFRPs.

The use of GFRPs allows for the aircraft to have impressive aeronautical capabilities, from landing and hovering like a helicopter while also being able to reorient its rotors midair to fly like a turboprop aeroplane. These aeronautical capabilities are due to the lightweight and adequate strength of GFRPs to tolerate high centrifugal sources while remaining slightly flexible (Joshi et al., 2016). GFRPs have also been noted to be used for parts of aircraft tails such as the fin/fuselage fairings, fixed leading, spoilers, ailerons, wheel doors, trailing-edge bottom access panels, trailing-edge flaps, deflectors, fuselage belly skins, and flap-track fairings, primary gear leg fairing doors, rudders, elevators, and nacelles (Muhammad et al., 2021; Sathishkumar et al., 2014). For example, in engine intake manifolds, GFRPs allow for a 60% reduction in weight, improved surface quality and aerodynamics, and a reduction in components as GFRPs allow for combining parts and forms into simpler moulded shapes compared to intake manifolds made from overcast aluminium (Masuelli et al., 2013).

The Boeing Stratocruiser long-range airliner achieved 20% weight savings over metal ducting using GFRPs (Boyer et al., 2015). The B727 aircraft also utilised GFRPs for radomes and fairing panels, with its successor, the B737 aircraft, utilising GFRPs in hot areas, radomes, fairings, and control-surface cover panels (Boyer et al., 2015). The B747 aircraft also utilised GFRPs in similar applications but on a much larger scale (Boyer et al., 2015). Aside from aircraft construction in the aerospace industry, GFRPs have also been widely used in ground-handling equipment (Sathishkumar et al., 2014).

4.1.2.2 Sustainability

Recyclability and reusability of GFRPs present notable challenges and opportunities as they are the most widely used FRPs (Rani et al., 2021). GFRPs have a notable presence in the aerospace industry, with glass fibres accounting for 65% of profits produced by FRP material sales (Tao et al., 2023). Therefore, with the growing concerns for environmental sustainability, exploring the methods of recycling and reusing GFRPs is critical. GFRPs comprise a majority of recycled composites, accounting for around 98% in weight (Gutiérrez et al., 2013; Oliveux et al., 2015). They are a significant material in the composite market, with a market share of over 95% (Tao et al., 2023). Due to the increasing amount of applications and large market size, there is pressure to develop recycling techniques for CFRPs and GFRPs (Scaffaro et al., 2021). However, GFRPs are discarded in massive volumes (Rani et al., 2021). More than two million metric tonnes of GFRP waste are projected to be created annually in the United States alone (Tao et al., 2023). This waste mainly comprises residues from the production process and end-of-life (EOL) products (Tao et al., 2023). Therefore, recycling and reusing GFRPs can decrease their detrimental influence on the environment and improve sustainability (Rani et al., 2021).

One of the main limitations in the reusability of GFRPs lies in the difficulty of separating the glass fibres from the polymer matrix without compromising the fibre's structural integrity, which has resulted in most GFRP waste being disposed of in landfills or incinerated (Tao et al., 2023). The difficulties in recycling GFRPs stem from covalent intermolecular chemical crosslinking polymer chains in the polymer matrix, mainly thermoset (Rani et al., 2021). Since FRPs are made up of a combination of different materials, it is difficult to separate these materials (Tao et al., 2023).

Traditional waste treatment processes like landfilling and incineration are increasingly restricted and banned worldwide (Tao et al., 2023). These processes are not a sustainable solution to GFRP waste because of their environmental impact, with landfills and mechanical recycling also having no economic efficiency of investment after ten years (Tao et al., 2023). According to Cost-Benefit Analysis (CBA) and Benefit Cost Ratio (BCR) analyses, reusing recycled Glass Fibres (rGFs) can reduce the total investment required and generate a positive cash flow (Tao et al., 2023). As recycling techniques such as landfilling and incineration pose a significant environmental concern, various recycling methods have been developed to reuse GFRPs (Tao et al., 2023).

Compared to other composite materials, GFRPs have some inherent advantages regarding environmental impact but also face significant hurdles regarding efficient recycling processes. However, because of the significant loss of their properties and characteristics, rGFs cannot be reused in the same high-performance and high-value applications such as those in the aerospace industry (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021; Tao et al., 2023). Moreover, in recycling GFRPs, low-cost recycling methods are utilised due to the lower price of VGFs (Farinha et al., 2019; Krauklis et al., 2021; Naqvi et al., 2018; Tao et al., 2023). Therefore, it is crucial to further research in reusing recycled GFRPs and rGFs (Tao et al., 2023).

Mechanical recycling is one of the most widely used techniques for recycling GFRPs and is noted as a suitable recycling alternative (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021). Compared to recycling CFRPs, mechanical recycling techniques are more commonly used for recycling GFRPs (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021). Mechanical recycling techniques are more suited for GFRPs than pyrolysis or solvolysis since the glass fibres are more prone to damage from the thermo-chemical processes (Oliveux et al., 2015). Furthermore, these techniques are more feasible for recycling GFRPs due to the reduced energy consumption and cost (Tao et al., 2023). Compared to traditional ways of disposing of GFRP waste, such as landfilling or incineration, mechanical recycling is a more efficient and environmentally sustainable way to recycle GFRPs (Rani et al., 2021). Moreover, industrialised applications of mechanical recycling techniques already primarily exist for GFRPs (Oliveux et al., 2015). Mechanical recycling for GFRPs is usually done in-house by some manufacturers; however, this only concerns production waste and not EoL GFRP waste (Oliveux et al., 2015). EoL GFRP waste is, therefore, more often landfilled (Oliveux et al., 2015).

While a majority of GFRPs are recycled using mechanical recycling techniques, rGFs recycled from these techniques

are noted to be discontinuous and cannot be used for the same high-value applications as those in the aerospace industry (Karuppannan et al., 2020; Tao et al., 2023; Yazdanbakhsh et al., 2018; Zhou et al., 2021). rGFs and rCFs recovered from mechanical recycling techniques have lower mechanical and physical properties, namely lower strength and reduced size of fibres (Rani et al., 2021). The lower mechanical properties make recycled GFRPs from mechanical recycling unsuitable for high-performance and high-load structural applications (Rani et al., 2021). Therefore, rGFs recycled from mechanical recycling processes are typically reincorporated into new composites or used in the construction industry in asphalt or cement (Conroy et al., 2006; Pickering et al., 2006b; Pimenta et al., 2011). Another viable option is repurposing and incorporating rGFs into the concrete through powders, fibres, and aggregates (Farinha et al., 2019; Tao et al., 2023; Zhou et al., 2021). rGFs can be mixed in with concrete to replace aggregates partially or as a reinforcing element (Tao et al., 2023). Reusing rGFs in this way has the potential to be a long-term and sustainable solution to manage GFRP waste by reducing the environmental impacts of GFRP waste, with efforts to commercialise rGFs in concrete since the last decade (Tao et al., 2023). As these recycled fibres usually represent low-value applications, mechanical recycling is used more for GFRPs (Pimenta et al., 2011). However, reusing rGFs recovered from mechanical recycling processes in Bulk Moulding Compounds (BMCs) has recently been shown to be more mechanically sustainable (Rani et al., 2021).

Thermochemical recycling processes such as pyrolysis and solvolysis are another option for recycling GFRPs. Pyrolysis and fluidised beds result in higher net benefits than landfills and mechanical recycling due to current market demands, the high value of recovered short fibres, and energy recovery (Tao et al., 2023). However, these processes are usually unsuitable for recycling GFRPs as they damage the glass fibres upon recycling (Oliveux et al., 2015). Pyrolysis and solvolysis significantly damage reinforcement, even at low concentrations (Oliveux et al., 2015). The pyrolysis process significantly deteriorates the mechanical properties, such as lower ultimate tensile strength and more brittle failure mode of rGFs than those recovered from mechanical recycling (Rani et al., 2021). rGFs from pyrolysis have been noted to retain less than 50% of their mechanical properties at the minimal temperature of 400°C (Oliveux et al., 2015; Rani et al., 2021). rGFs recovered from pyrolysis have been noted only to have 60-70% of the strength of vGFs (Rani et al., 2021). rGFs recycled through pyrolysis have exhibited a reported average of a 40-50% drop in tensile strength from the flexural modulus, flexural strength, and Charpy impact strength compared to vGFs (Cunliffe et al., 2003; Rani et al., 2021). The reduction of strength in rGFs recovered this way is due mainly to the defects, the nature of the structure of GFRPs, where it cannot retain its structure under the high-temperature degradation process in pyrolysis, and developments of new flaws during the heat treatment process (Mehdikhani et al., 2019; Naqvi et al., 2018; Rani et al., 2021).

From an economic point of view, recovered rGFs from pyrolysis are not viable for reuse in high-value applications due to their low market potential (Naqvi et al., 2018). Furthermore, solvolysis recycling for GFRP waste is only investigated on a small scale and has not reached widespread industrial applications (Mattsson et al., 2020; Oliveux et al., 2011; Oliveux et al., 2013; Tao et al., 2023). Therefore, thermochemical recycling processes are not economically viable for GFRPs because of the drastic reduction in mechanical properties of rGFs and the low cost of vGFs (Oliveux et al., 2015; Rani et al., 2021).

The fluidised bed process is another technique for recycling GFRPs. The fluidised bed process extracts the thermoset polymer matrix from the reinforcement fibres, in this case, glass, by a thermal or oxidation process to produce clean fibres (Rani et al., 2021). This process involves heating a silica sand bed at a high-temperature range of around 400-650°C and fluidising it with hot air to decompose chopped GFRPs (Rani et al., 2021). The organic parts of the GFRP, such as the sand particles, fillers, and fibres, are vaporised by the hot air and conveyed in a stream of air with silica particles (Rani et al., 2021). The resin part provides heat and energy during the process, while the fillers and fibres can be recovered (Rani et al., 2021). Since the melting point of the glass is higher, with a melting temperature range between 1400-1600°C, the glass fibres can be recovered (Rani et al., 2021). Dough Moulding Compound (DMC) samples consisting of a variation of 50% rGFs recovered using the fluidised bed process with 50% vGFs performed better in flexural and tensile strength than rGFs recovered from other recycling techniques (Rani et al., 2021). It has also been noted that heat does not significantly influence Young's modulus of rGFs recovered this way--making it comparable to vGFs (Rani et al., 2021). However, GFRPs recycled through this process have significantly decreased strength (Rani et al., 2021). Comparing the mechanical properties of rGFs with vGFs, recovered rGFs from the fluidised bed process have been noted to exhibit a 50% reduction in tensile strength with constant stiffness (Pickering et al., 2000; Rani et al., 2021). The reported possible cause for the reduction in the strength of rGFs in this way was the deterioration of the fibre length and a large number of defects on the surface of these rGFs (Rani et al., 2021). In order to maximise the residual strength of rGFs from this process, the operating temperature should be low in the fluidised bed recycling method (Rani et al., 2021).

Compared to CFRPs, GFRPs present better opportunities for increased sustainability. Regarding energy cost and economic viability, the fabrication of GFRPs is less costly than CFRPs (Rani et al., 2021), For example, recycling GFRPs uses around 13-54 MJ/kg for production compared to CFRPs, which require around 183-704 MJ/kg (Rani et al., 2021). Additionally, mechanical recycling techniques are more suited for GFRPs than CFRPs. However, compared to recycling CFRPs, the economic balance is more vague as rGFs would struggle to be reused as commonly used fillers are readily available at a low cost (Oliveux et al., 2015).

The future of GFRP recyclability and reusability depends on continued research and innovation in recycling technologies to improve sustainability (Tao et al., 2023). Currently, no recycling processes are available to recover rGFs with the same characteristics and properties as vGFs at a competitive price,

as the price of vGFs is low (Oliveux et al., 2015). rGFs can replace small quantities of vGFs in products; however, at higher concentrations, the recycling process becomes economically and environmentally unviable, particularly when employing thermolysis or solvolysis techniques (Oliveux et al., 2015). Recycling processes for GFRPs have to be economically viable with the low cost of vGFs (Rani et al., 2021). However, rGFs can be further utilised and reused in lower-value applications as a more limited alternative than vGFs (Rani et al., 2021). Therefore, developing alternative ways to utilise GFRP waste efficiently is crucial to improving the material's sustainability (Tao et al., 2023). Recycling techniques addressing EOL GFRP waste are essential to the sustainability of GFRPs (Naqvi et al., 2018). Moreover, enhancing the economic viability of recycling processes and improving the quality of rGFs are critical steps toward making GFRPs a more sustainable choice in aerospace and other high-performance applications.

4.1.2.3 Limitations

GFRPs have several limitations, such as their relatively lower mechanical properties than CFRPs, limiting their use in primary structural applications. They are not as strong as CFRPs and are more suited for secondary and interior applications where cost savings are also a consideration (Masuelli et al., 2013; Joshi et al., 2016; Zhang et al., 2022). The production and processing of GFRPs, while less expensive than CFRPs, still involve significant costs, particularly for high-quality aerospace-grade composites using glass fibres such as S-glass. Moreover, GFRP production is still relatively complex, involving several steps to ensure optimal material properties. Like CFRP production, GFRP production involves weaving, pre-impregnating fibres, and precise temperature and pressure control. This multi-step process and the need for precise control of processing parameters add to the complexity of GFRP production. Machining and repairing GFRP components can also be challenging due to the abrasive nature of glass fibres, which can wear down cutting tools and require specialised equipment (Boyer et al., 2015; Joshi et al., 2016; Masuelli et al., 2013).

Furthermore, GFRP recycling and end-of-life disposal are less developed than metals and other composites, posing environmental concerns. The increasing amount of EOL GFRP waste requires suitable recycling and reusing methods to address sustainability (Tao et al., 2023). Current recycling methods for GFRPs often result in a significant loss of material properties, which limits the reuse of recycled fibres to low-value applications (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021; Tao et al., 2023).

4.2 Aluminium Alloys

Aluminium Alloys (AAs) are alloys in which aluminium is the primary metal, supplemented with other elements such as copper, magnesium, manganese, silicon, and zinc to enhance its properties. Aluminium alloys, heat-treatable or non-heat-treatable, are wrought alloys classified by the following: Copper—2XXX; Magnesium and Silicon—6XXX; Zinc—7XXX (Rambabu et al., 2017). Among these, the 2XXX (copper-containing) and 7XXX (zinc-containing) alloys are particularly notable for their applications in the aerospace industry and start with 2024 and 7075, respectively (Boyer et al., 2015). These alloys have been modified to improve their strength and toughness, with the development of newer alloys like 7150 and 7055, which improve tempers, higher strength, and corrosion resistance (Boyer et al., 2015).

AAs have been extensively used throughout the history of the aerospace industry due to their notable performance characteristics (Nagaraju et al., 2023). The widespread adoption of AAs in aerospace applications is due to their high specific strength and stiffness, high strength-to-weight ratios, corrosion resistance, excellent electrical and thermal conductivity, and manufacturing versatility (Huda et al., 2013; Nagaraju et al., 2023; Rambabu et al., 2017; Soo et al., 2018; Zhang et al., 2018; Zhang et al., 2019; Zhang et al., 2022). AAs are also active in the galvanic series and cost-efficient as it is one of the most easily fabricated high-performance materials, resulting in relatively low manufacturing costs (Boyer et al., 2015; Heinz et al., 2000; Rambabu et al., 2017). They are much less costly and complex to fabricate than composites for commercial aircraft due to widely available high-speed milling machines and high feed rates (Heinz et al., 2000; Huda et al., 2013).

In aerospace, AAs are used in aircraft's upper and lower wing, fuselage, and empennage sections, within various aircraft programs, such as the B777 and B737 aircraft (Heinz et al., 2000; Rioja et al., 2012; Starke et al., 1996). For example, the 5083 AA were used in the wing steps of the B777 (Nagaraju et al., 2023). Apart from commercial aircraft, AAs also play a significant role in fighter aircraft, comprising up to 30% of some aircraft (Campbell et al., 2011; Rambabu et al., 2017). The floor of the Boeing C17 military aircraft also utilised AAs, which reduced the number of joints by a factor of four and allowed for significant cost savings (Heinz et al., 2000). AAs can also be used in various structural parts of supersonic aircraft, with another notable application of AAs in the Concorde (Huda et al., 2013). They were chosen as the basis for the Concorde mainly because of the choice of Mach 2 as its designed cruise speed (Huda et al., 2013). Moreover, the Saturn IB launch vehicle had fuel tanks made with 5456-H116 AAs, with a specific yield strength of 96 MPa/g/cm3 (Rioja et al., 2012). The more recent usage of 2195-T8M4 alloys in the fuel tanks of the space shuttle had a specific yield strength of 211 MPa/g/cm3 (Rioja et al., 2012). However, AA usage has mainly been reduced in aerospace applications. For example, AAs comprised approximately 80% of the structural weight of earlier aircraft but are now only about 25% of the more recently developed B787 aircraft (Boyer et al., 2015).

4.2.1 Performance

AAs are widespread in the aerospace industry because of their versatility in various applications while maintaining favourable mechanical properties and weight (Nagaraju et al., 2023; Zhang et al., 2022). The strength of AAs varies depending on the elements they are coupled with, but they have higher strength than structural steel (Zhang et al., 2022). For instance, AAs have a yield strength of 306-520 MPa for 2XXX series alloys and 496-776.5 MPA for 7XXX series alloys (Zhang et al., 2018). The strength of AAs was improved throughout

the decades through advancements in the thermomechanical processing of the alloys (Boyer et al., 2015). AAs are also considered lightweight compared to other alloys due to the density of aluminium, its primary material (Rambabu et al., 2017). For example, the density of aluminium is 2.69 g/cm3, around one-third that of conventional steel at 7.83g/cm3 (Rioja et al., 2012; Zhang et al., 2018; Zhang et al., 2022). The manufacturing versatility of AAs stems from the fact that many variations of AAs are developed to suit particular product forms and applications (Rambabu et al., 2017). The versatility allows for a range of AAs to optimise and trade-off specific properties, giving them the ability to be optimised for particular aerospace applications (Rambabu et al., 2017). These characteristics make AAs an extensively used material in aircraft structures and have replaced steel as the metal of origin for aviation structural components (Nagaraju et al., 2023). Many variations of AAs are developed to suit specific applications in the aerospace industry (Rambabu et al., 2017). In particular, the 2XXX and 7XXX series alloys are the most extensively used AAs in the aerospace industry.

2XXX series AAs have high flexibility, strength, and temperature resistance (Huda et al., 2013; Zhang et al., 2018). These 2XXX series AAs are alloyed with copper and are heat-treatable to a strength comparable to steel (Zhang et al., 2018). They are lightweight yet strong, with a density ranging from 2.59-2.84 g/cm3 while having a yield strength between 325-483 MPa and ultimate tensile strength ranging from 476-520 MPa (Davis et al., 1993; Li et al., 2023; Rambabu et al., 2017; Zhang et al., 2018). These alloys have high flexibility with an elasticity modulus ranging from 72.4-73.8 GPa (Davis et al., 1993; Rambabu et al., 2017). 2XXX series AAs also have higher damage tolerance, fatigue resistance, and cost-effectiveness than other AA series alloys (Huda et al., 2013; Zhang et al., 2018).

These characteristics make 2XXX series AAs a popular material in the industry. For example, the high flexibility and temperature resistance characteristics allowed 2650-T8 AAs to be selected for military aircraft wings (Huda et al., 2013). Moreover, 2XXX series AAs are commonly used for fuselage, pressure cabin skins, lower wing covers, tactical aircraft fuselage panels, tactical aircraft bulkheads, lower wing stringers, and pressure cabin stringers utilised sheets, plates, and extrusions because of their properties (Li et al., 2023; Rambabu et al., 2017). For example, the 2024 AA have been widely used as aircraft fuselage material as damage tolerance is a significant factor (Li et al., 2023; Zhang et al., 2018). In addition, the space shuttle's fan cases, external fuel tank, and the shuttle remote manipulator system components for NASA were manufactured using 2219 AAs (Bharath et al., 2022; Boyer et al., 2015; Nagaraju et al., 2023). Parts of the space shuttle orbiter also used 2024, 2124, and 2219 AAs, where weldability, high strength, fracture toughness, and extreme temperature endurance were required (Nagaraju et al., 2023). 2XXX series AAs were also chosen for parts subjected to high temperatures (Li et al., 2023; Nagaraju et al., 2023). For example, the 2419-T851 AA was found in airframes at temperatures ranging from 100C to 180C (Nagaraju et al., 2023). Compared to 7XXX series AAs, 2XXX series AAs are generally superior under constant amplitude loading for tactical fighter aircraft (Rambabu et al., 2017; Wanhill et al., 1994). However, 2XXX series alloys exhibit poor corrosion resistance, thermal stability, and low fracture toughness (Li et al., 2023; Rioja et al., 2012). For example, the relatively low yield strength of 2024 AAs limits their use in high-stress regions in aircraft (Zhang et al., 2018).

7XXX series AAs, aluminium alloyed with zinc, are high-strength AAs, though they exhibit lower fracture toughness, damage tolerance, and corrosion resistance characteristics than the 2XXX series AAs (Zhang et al., 2018). These 7XXX series AAs are heat-treatable to the highest strength compared to other AAs (Zhang et al., 2018) and consequently have significantly higher strengths and superior fracture toughness than 2XXX series AAs (Li et al., 2023; Rambabu et al., 2017). For example, 7XXX series AAs have a yield strength between 450-505 MPa and ultimate tensile strength ranging from 510-570 MPa (Davis et al., 1993; Rambabu et al., 2017). However, they are denser and less flexible than 2XXX series AAs, with a density ranging from 2.80-2.83 g/cm3 and an elasticity modulus between 70.3-71.0 GPa (Davis et al., 1993; Rambabu et al., 2017). Currently, the highest strength 7XXX series AAs commercially available are those made primarily of aluminium, zinc, magnesium, and copper and exhibit higher general and stress corrosion resistance (Davis et al., 1993; Li et al., 2023; Rambabu et al., 2017).

The 7XXX series are AAs widely used in various aerospace applications because of their superior strength and fracture toughness characteristics. In the aerospace industry, plates, forgings, and extrusions made from 7XXX series AAs are used for internal fuselage structures, upper wing covers, spars, ribs, wing and fuselage attachments, fuselage stringers and frames, upper wing stringers, floor beams, seat rails, and other internal structures (Rambabu et al., 2017). The 7055-T7751 is the strongest AA used in the aerospace industry and is mainly used for upper wings (Rioja et al., 2012). This alloy has a specific compressive strength of 229 MPa/g/cm3, which is more than five times stronger than conventional AAs (Rioja et al., 2012; Starke et al., 1996). In 7XXX series AAs, the 7075 AA is the most used in applications where strength is the primary consideration. 7075-T6 AAs have a 2.81 g/cm3 density, yield strength of 505-520 MPa, and ultimate tensile strength of 575 MPa (Huda et al., 2013; Li et al., 2023; Zhang et al., 2018). Because of these characteristics, upper-wing skins, stringers, and stabilisers used 7075-T6 AAs (Dursun et al., 2014; Zhang et al., 2018). Moreover, 7050 AAs were used in the compression structure of the F/A–18 fighter jet and the B777 aircraft (Li et al., 2023). 7050-T7451 AAs were also developed and successfully used for corrosion-critical aerospace applications (Rioja et al., 2012). Similarly, the 7050-T7351 AA was developed to fit the need for a material with high strength in thick-section products, good resistance to SCC and exfoliation corrosion, and good fracture toughness and fatigue characteristics (Rambabu et al., 2017). However, 7075 AAs have low fracture toughness, damage tolerance, and corrosion resistance, which have limited the use of 7075 AAs in the aerospace industry (Rambabu et al., 2017; Starke et al., 1996; Zhang et al., 2018). Thicker-section airframe components made from 7XXX series alloys

like 7075-T6 AAs and 7079-T6 AAs were more susceptible to SCC with anisotropy in the short transverse direction (Rambabu et al., 2017). These issues have led to other 7XXX series AAs developed from the 7075 AA. The 7085 AA is a recently developed alternative for 7075 AAs in aerospace applications because of its high yield strength of 504 MPa and better damage tolerance of 44 MPa m1/2 (Antipov et al., 2012; Karabin et al., 2009; Li et al., 2023; Zhang et al., 2018). It is also the latest alloy developed from the 7050-T7351 AA and is primarily used for making large forgings, such as wing girders and ribs, for the monolithic and large structure of the A380 aircraft (Li et al., 2023; Rambabu et al., 2017). Moreover, 7475 AAs were developed from 7075 AAs to improve fracture toughness (Rambabu et al., 2017). The 7475 AAs have a higher fracture toughness of 52 MPa m1/2 and finer grain size than conventional 7075 AAs (Zhang et al., 2018). In general, the 7XXX series AAs are superior to the 2XXX series alloys. These are evident in applications like manoeuvre spectrum loading representatives for tactical fighter aircraft (Rambabu et al., 2017; Wanhill et al., 1994).

4.2.2 Sustainability

With the extensive use of AAs in the aerospace industry and the growing emphasis on sustainability, it is imperative to investigate effective AA recycling and reusing methods. While AAs are currently one of the most recycled metals, technical and economic issues hinder efficient AA recycling (Soo et al., 2018). Currently, recycling aluminium utilises around 2.8 kWh of energy and emits roughly 0.6 kg of CO2 per kilogram of metal (Das et al., 2008; Das et al., 2010). Therefore, recycling aluminium saves around 95% of the energy and environmental emissions (Das et al., 2010b). Recycling through the production of secondary AAs also results in emissions of only about 4% of that in primary aluminium production (Das et al., 2008). Currently, recycled Aluminium Alloys (rAAs) can be reused for non-critical aircraft components in most aircraft, such as stiffeners, flaps, and other relatively low/moderately stressed components made of sheet, plate, or extrusions (Das et al., 2008). There are also opportunities to directly reuse recycled AAs in 2024 and 7075 similar alloys (Das et al., 2010a). With heat treatment and precipitating ageing, the physical properties of the remelt alloys are similar to the 2024 and 7075 AAs and can be utilised in non-fracture-critical aerospace applications (Das et al., 2010a).

However, the annual global scrap surplus is predicted to proliferate to 5.4 million tonnes of aluminium waste in 2030 and around 8.7 million tonnes in 2040 due to complex recycling processes (Van den Eynde et al., 2022). Thousands of EOL aircraft have been left in waste sites while the demand for rAAs increases because of the complex recycling processes and other economic factors (Das et al., 2010a; Das et al., 2010b). Airbus projects that 40,000 aircraft will come out of service and become waste in 20 years (Eckelman et al., 2014). These discarded EOL aircraft are a significant potential source of valuable metal that can be recycled and reused (Das et al., 2010a). A demonstration from Airbus revealed that 85% of the total mass of materials in EOL aircraft can be recycled, with a majority of it being AAS (Eckelman et al., 2014). However, they are usually selectively dismantled for spare parts as recertified aircraft components have greater economic value than AA scrap (Das et al., 2010b). Therefore, with the exponential growth in global demand, the sustainable management of AAs has become an increasingly crucial problem and must be addressed (Soo et al., 2018).

The purity level of the rAA scrap influences the extent to which the physical properties of rAAs are retained through recycling, and it is one of the major factors for efficient recycling (Soo et al., 2018). It is difficult to remove the impurities or tramp element contaminants that affect the quality of the rAAs because of aluminium's relatively low melting point (Soo et al., 2018). From the contamination of typical alloying elements of aluminium, only magnesium and zinc can be removed to an acceptable extent from remelting (Paraskevas et al., 2015). The residual elements remaining and the purification of the melt are technically challenging to achieve (Paraskevas et al., 2015). Scrap preparation or separating processes like shredding, melting, oxidation, landfilled residues, and slag waste through AA recycling contribute to the losses in the purity levels of the rAAs. These quality losses occur as the quality in the composition of the produced secondary metal does not match the input material (Paraskevas et al., 2015). Engine components are manufactured with high-purity materials because of the stringent tolerance for failure, which is why rAAs cannot be used due to the impurity risk (Eckelman et al., 2014). The potential buildup of elements like chromium, zinc, and vanadium, along with iron, magnesium, and silicon, must be addressed to improve the properties of rAAs. This factor is especially significant as newer AAs like the 2124, 2048, 7050, and 7085 AAs begin to be recycled (Das et al., 2010a). Minimal refining strategies exist to remove impurities or undesired alloying elements from the contaminated AA scrap (Zhang et al., 2022). While post-electrolysis processes can recover most residual elements in remelted metals like copper, this process does not work for aluminium (Paraskevas et al., 2015). However, shredding the particles into smaller sizes can help decrease the presence of impurities from mechanical fastening joints and imperfect liberation and improve the scrap quality of aluminium from recycling processes (Soo et al., 2018).

In recycling AAs, it is crucial to consider pre-shred dismantling, separating, sorting, and categorising scrap parts based on alloy composition to improve remelting efficiency (Das et al., 2010a; Eckelman et al., 2014). Dismantling and presorting scrap would aid in maximising the value of rAAs (Das et al., 2010a). For example, 2XXX and 7XXX series alloys must be sorted before remelting to help maximise efficiency and reduce impurities (Das et al., 2010a). Techniques to improve this can include dismantling aircraft into logical component groups, as these parts are typically made with alloys of the same series (Das et al., 2010a). For example, landing gears, engine nacelles, tail sections, and flaps can be presorted (Das et al., 2010a). Understanding the dynamics of scrap generation in other economic sectors is vital as they may affect global supplies of aviation-relevant scrap (Eckelman et al., 2014). Therefore, dismantling and presorting strategies are essential to improve AA recycling efficiency and yield (Das et al., 2008). An example of presorting can involve sorting and separating the

AAs by density after shredding and magnetic separation (Soo et al., 2018). Processed AA scrap is then remelted, with fluxing being the most widely used form of melt purification treatment in AA recycling. This method can remove more than half of the magnesium content from AA scrap by remelting with a salt flux treatment (Mashhadi et al., 2009; Paraskevas et al., 2015).

The most widespread recycling processes that address the challenges of recycling AAs are dilution or down-cycling (Soo et al., 2018; Paraskevas et al., 2015). Refining limitations and contamination challenges in recycling AAs have been addressed by diluting the contaminants with primary aluminium or down-cycling to rAAs with lower purity requirements (Paraskevas et al., 2015). Therefore, AA recycling is performed in a cascade recycling chain and is used in applications with lower purity requirements (Paraskevas et al., 2015).

Dilution refers to diluting the impurities and contaminants in recycled AA waste with higher-purity metal inputs to reduce the alloying level (Zhang et al., 2022; Paraskevas et al., 2015). During remelting, there is a loss in dilution due to the need to dilute the residual element concentration with the primary aluminium (Soo et al., 2018). Dilution losses occur when high-purity metal is required to lower the contaminant and residual concentration to the limits of the target alloy (Paraskevas et al., 2015). These losses can result in the underutilisation of scrap depending on the target rAA (Paraskevas et al., 2015). Because of this, dilution is particularly suited for recycling AAs and considers the limited scrap availability and dilution agent for wrought alloys (Paraskevas et al., 2015). Zinc, the primary alloying element in the 7XXX series AAs, can be recovered using dilution (Ohtaki et al., 2000; Paraskevas et al., 2015). Dilution and cascade recycling processes can be more easily implemented into high-volume single alloy scrap streams where the demand for the specific alloys is also high (Paraskevas et al., 2015). This process can effectively balance demand and overcome refining limitations by considering the limited scrap availability and high demand for both wrought and cast alloys (Paraskevas et al., 2015).

Down-cycling is the recycling and reusing recycled material that is of lower quality and functionality than virgin material in applications with lower purity requirements (Paraskevas et al., 2015). It refers to the cascade accumulation of residuals and impurities to AAs with lower purity requirements using higher-purity scrap streams to produce lower-purity products (Paraskevas et al., 2015). For example, this can include the transition from mixed wrought alloys to cast-quality alloys (Paraskevas et al., 2015). Down-cycling AA scrap to cast alloys is a common recycling strategy due to the high demand for these alloys (Paraskevas et al., 2015). However, the future market for these products is not guaranteed, and it is not a sustainable solution for recycling and reusing AAs (Paraskevas et al., 2015). There has also been a growing concern throughout recent years regarding the sustainability of cascade recycling for AAs (Paraskevas et al., 2015). Therefore, minimising the down-cycling of AAs and primary aluminium needed for dilution recycling can help mitigate these challenges and contribute to more sustainable and efficient use of AAs (Paraskevas et al., 2015). Economically, the increased cost of primary aluminium from dilution and reduced product value from down-cycling are incentives towards developing more efficient recycling methods that preserve the quality and purities of rAAs (Paraskevas et al., 2015).

Despite the considerable recycling potential of AAs, there is currently a lack of studies examining the environmental benefits of AA recycling in the aerospace industry (Eckelman et al., 2014). AA recycling methods like fractional crystallisation and unidirectional solidification are still developing. They are currently not viable for large-scale scrap purification from a technical and economic point of view (Paraskevas et al., 2015). The biggest challenge in recycling AAs involves preserving the economic value of the rAA compared to virgin Aluminium Alloys (vAAs) (Paraskevas et al., 2015). For example, melt purification processes for recycling aluminium are much more limited than other base metals like copper or steel (Paraskevas et al., 2015).

Furthermore, while rAAs can be reused for non-critical aircraft components, they are typically not designed based on fracture fatigue crack growth rates and fracture toughness parameters, as the alloys used in these fracture-critical areas still have to be fabricated using vAAs (Das et al., 2008). Numerous challenges exist in the cost-effective aircraft recycling of AAs (Das et al., 2008). These include identifying decision options for dismantling aircraft and optimising technologies for automated shredding, sorting, and remelting of particularly 2XXX and 7XXX series alloys as they have relatively high alloying elements, sometimes more than 10% (Das et al., 2008). Moreover, they are relatively high in alloying elements and may contain low minor elements to optimise fracture toughness (Das et al., 2010a). This is especially true for 2XXX and 7XXX series AAs as they are high in alloying elements like copper and zinc, and this is why these series AAs used in the aerospace industry are generally not recycled (Das et al., 2010a; Das et al., 2010b).

4.2.3 Limitations

Despite the advantages of AAs, they exhibit certain limitations in their physical properties and environmental sustainability. While AAs have high strength, they are also noted to have a low modulus elasticity and are susceptible to corrosion (Campbell et al., 2011; Rambabu et al., 2017). In particular, corrosion and fatigue cracking are a severe concern in aluminium commercial fuselage structures (Asyraf et al., 2022). Notable AAs susceptible to Stress Corrosion Cracking (SCC), which occurs under the combined action of a continuous tensile stress and a specific corrosive environment, are the 2XXX-T8XX, 7XXX-T6XX and 7XXX-T7XX series alloys (Rambabu et al., 2017). The low corrosion resistance is also why AAs typically require corrosion protection (Rambabu et al., 2017). Moreover, AAs usually have high anisotropy because of the nature of the crystal structure and the various processing methods used to produce AAs, which means that the physical properties of AAs differ when measured in different directions (Heinz et al., 2000; Huda et al., 2013; Nagaraju et al., 2023; Rambabu et al., 2017; Rioja et al., 2012; Zhang et al., 2018). However, significant

advancements have been made in improving AAs' static and fracture properties since they were first used in aerospace applications (Boyer et al., 2015). These were achieved by reducing impurities like iron and silicon and reducing coarse second-phase particles' volume fraction (Boyer et al., 2015). Improved purity levels led to more damage-tolerant variants of AAs (Boyer et al., 2015). For example, 2024 alloy progressed to 2124, 2224, and ultimately 2524 (Boyer et al., 2015). Another limitation of AAs is their numerous challenges in environmental sustainability and, as previously mentioned, in the cost-effective recycling of AAs (Das et al., 2008). For example, aluminium has an absolute emissions rate of 12.2kg CO2e/kg, with the 7075 AA having a noted GHG emission between 9-15 kg CO2e/kg (Eckelman et al., 2014). Moreover, primary aluminium production requires around 45 kWh of energy and emits 12 kg of CO2 for each kilogram of metal (Das et al., 2008; Das et al., 2010b; Paraskevas et al., 2015). Extracting primary aluminium has a substantial environmental impact because of the high energy consumption and waste generation compared to secondary aluminium processing (Soo et al., 2018).

5. FIGURES

Figure 1: Components Constructed from CFRPs on The Airbus A380 (Ramli Et Al., 2022)

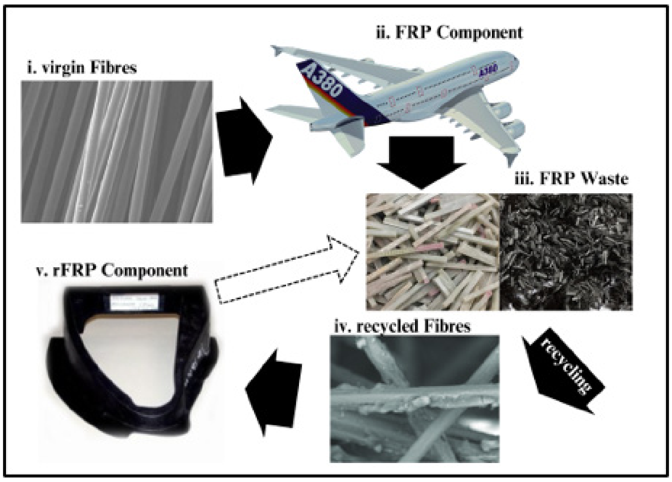

Figure 2: Closed Life-Cycle For FRPs (Pimenta Et Al., 2011)

6. DISCUSSION

The primary purpose of this paper is to explore how materials can tackle the strength-to-weight ratio requirements while addressing sustainability in aerospace applications. Given the increasing demand for strong yet lightweight materials while considering environmental sustainability in the aerospace industry, this research aims to identify and analyse materials that meet these critical requirements. The study contributes to the broader challenge of reducing the environmental impact of the aerospace industry while maintaining or improving the performance of aerospace applications. By focusing on CFRPs, GFRPs, and AAs, the study comprehensively assesses how these materials can balance high performance and sustainability, addressing one of the industry's most pressing issues.

This paper analysed the properties and applications of three key materials: Carbon Fibre-Reinforced Polymers (CFRPs), Glass Fibre-Reinforced Polymers (GFRPs), and Aluminum Alloys (AAs). The analysis focused on their strength-to-weight ratio, sustainability, and similar properties in aerospace applications. Regarding the sustainability aspects, the paper examined the recycling and reusability potential of these materials, which are crucial for addressing the environmental impact of the aerospace industry. However, a considerable gap remains in examining the environmental benefits of recycling in the aerospace industry (Eckelman et al., 2014).

CFRPs are among the newest and most extensively used materials in the aerospace industry (Tao et al., 2023). They offer high specific strength and stiffness, which allows for their use in high-performance aerospace applications (Huda et al., 2013; Nagaraju et al., 2023; Tao et al., 2023; Zhang et al., 2022). Moreover, they have a high strength-to-weight ratio while maintaining low density, allowing for an enhanced fuel economy and lower operational costs (Asyraf et al., 2022; Hegde et al., 2019; Huda et al., 2013; Muhammad et al., 2021; Nagaraju et al., 2023; Soutis et al., 2005). These physical and mechanical properties make CFRPs popular in high-performance aerospace applications such as supersonic aircraft and mainly in critical primary structures like fuselage and wing sections (Boyer et al., 2015; Huda et al., 2013; Joshi et al., 2016). Compared to metals, CFRPs are significantly more lightweight and have a density of three-fifths that of AAs (Zhang et al., 2018). CFRPs provide superior mechanical properties to GFRPs and AAs, making them the material of choice for applications where high strength-to-weight ratios are crucial.

However, technical and economic challenges are associated with the recycling and reusing of CFRPs. Therefore, addressing sustainability concerns for CFRPs is paramount. The complex manufacturing processes and difficulty separating the carbon fibres from its polymer matrix make recycling CFRPs challenging compared to other materials like AAs (Muhammad et al., 2021; Oliveux et al., 2015; Pimenta et al., 2011). Moreover, rCFs recovered from CFRPs significantly lose mechanical properties and can only be reused in non-critical aerospace components (Hegde et al., 2019; Oliveux et al., 2015). However, mechanical recycling can be suited

for CFRPs reinforced with lower-grade or short carbon fibres (Oliveux et al., 2015). These same issues are also why CFRPs are considerably more expensive to manufacture and recycle than GFRPs and AAs (Geier et al., 2019; Muhammad et al., 2021; Oliveux et al., 2015; Pimenta et al., 2011). Despite these challenges, the superior performance characteristics of CFRPs justify their use in high-performance aerospace applications. Further research and development must address technical, economic, and market-related issues in CFRP recycling to improve the sustainability of CFRPs (Muhammad et al., 2021; Pimenta et al., 2011).

GFRPs offer advantages in recycling and reusing as well as disadvantages in strength compared to CFRPs and AAs. While GFRPs have relatively high specific strength and stiffness while also having low density, their mechanical properties are far lower than those of CFRPs and AAs, which is why they are not suitable for primary structural components in aerospace applications like airframe and engine components (Boyer et al., 2015; Ferdous et al., 2020; Joshi et al., 2016; Kumar et al., 2016; Masuelli et al., 2013; Muhammad et al., 2021; Nagaraju et al., 2023; Rajak et al., 2021; Sathishkumar et al., 2014; Shivanagere et al., 2018; Tao et al., 2023; Zhang et al., 2022). However, GFRPs are much more cost-effective and durable than CFRPs, making them a more viable option for secondary structures and interior components (Joshi et al., 2016; Masuelli et al., 2013; Sathishkumar et al., 2014; Zhang et al., 2022). While GFRPs may not be optimal for more high-performance aerospace applications, they are still crucial in significant secondary structures and notable for improved sustainability in the industry.

Similar to CFRPs, GFRPs face recycling challenges involving separation and mechanical property loss, although they are more recyclable than CFRPs as they consume less energy and are less costly (Rani et al., 2021). Further research is needed to overcome the recycling issues as current methods often result in a significant loss of material properties, which limits the reuse of recycled fibres to low-value applications (Oliveux et al., 2015; Pimenta et al., 2011; Rani et al., 2021; Tao et al., 2023). The more cost-effective and efficient recycling of GFRPs makes them more sustainable than CFRPs. However, similar to CFRPs, the recyclability and reusability of GFRPs must continue to be explored to further address technical and environmental challenges.

Aluminum Alloys (AAs), particularly the 2XXX and 7XXX series AAs, have been a staple in aerospace applications for decades due to their high specific strength and stiffness, excellent strength-to-weight ratios, corrosion resistance, and ease of manufacturing (Huda et al., 2013; Nagaraju et al., 2023; Rambabu et al., 2017; Soo et al., 2018; Zhang et al., 2018; Zhang et al., 2019; Zhang et al., 2022). These characteristics make AAs an extensively used material in fuselage, wing, and empennage sections in various aircraft programs (Heinz et al., 2000; Rioja et al., 2012; Starke et al., 1996). However, some AAs, like the 2XXX series AAs, cannot match the strength-to-weight ratios of CFRPs (Li et al., 2023; Rioja et al., 2012; Zhang et al., 2018). Furthermore, AAs are particularly susceptible to corrosion and fatigue cracking compared to other materials (Campbell et al., 2011; Rambabu et al., 2017). However, significant advancements have been made to improve these AA shortcomings (Boyer et al., 2015).

These AAs are a reliable alternative to CFRPs and GFRPs, with their main advantage encompassing improved recyclability. AAs are currently one of the most recycled aerospace materials as they are easily recyclable and have well developed and widespread recycling infrastructure (Das et al., 2010a; Eckelman et al., 2014; Soo et al., 2018). However, there are still challenges and a need for feasible processes for retaining the same purities and subsequent mechanical properties of vAAs in rAAs, which is why rAAs are usually down-cycled for non-critical components (Eckelman et al., 2014; Paraskevas et al., 2015; Soo et al., 2018; Zhang et al., 2022). Further research should focus on improving cost-effective recycling and maintaining the purity of rAAs in order to improve the sustainability of AAs (Das et al., 2008; Eckelman et al., 2014; Soo et al., 2018).

7. CONCLUSION

This study focused on evaluating the current materials available and how they tackle the requirements of strength-to-weight and sustainability of aerospace applications. By analysing the properties and applications of CFRPs, GFRPs, and AAs, the study addressed the need to balance high-performance demands with environmental sustainability in the aerospace industry.

These findings highlight the trade-offs between performance and sustainability in aerospace material selection. CFRPs' superior mechanical properties justify their use in critical applications, but their sustainability issues must be addressed. GFRPs and AAs provide more sustainable alternatives, especially in less critical applications. The study suggests that improving the recyclability of CFRPs and enhancing the recycling processes for AAs are crucial for reducing the aerospace industry's environmental impact.

However, the primary limitation in this paper is its focus on only three materials, which may not capture the full spectrum of available options for optimising strength-to-weight ratios and sustainability in aerospace applications. Further research into the latest advancements like hybrid or nanocomposites materials could offer further insights into material optimisation.

Future research should focus on advancing recycling technologies and methods for composite materials to enhance their sustainability by maintaining mechanical properties while being economically feasible. Further advancements in Aluminum Alloy recycling processes are also necessary to improve their sustainability, particularly in maintaining material purity and mechanical properties. The aerospace industry can achieve a more sustainable and efficient future by addressing these areas and meeting performance and environmental goals.

In conclusion, strategic material selection is critical to balancing performance and sustainability in aerospace engineering. By addressing the recyclability of CFRPs and

refining AA recycling processes, the aerospace industry can make significant strides toward a more sustainable future, ensuring that high-performance materials also contribute to environmental responsibility.

REFERENCES

1. Al-Lami, A., Hilmer, P., & Sinapius, M. (2018). Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry. Aerospace Science and Technology, 79, 669-678.
2. Allred, R. E., Gosau, J. M., & Shoemaker, J. M. (2001). Recycling process for carbon/epoxy composites. In 46 th International SAMPE Symposium and Exhibition (pp. 179-192).
3. Antipov, V. V., Senatorova, O. G., Tkachenko, E. A., & Vakhromov, R. O. (2012). High-strength Al–Zn–Mg–Cu alloys and light Al–Li alloys. Metal Science and Heat Treatment, 53(9), 428-433.
4. Asyraf, M. R. M., Ilyas, R. A., Sapuan, S. M., Harussani, M. M., Hariz, H. M., Aiman, J. M., ... & Asrofi, M. (2022). Advanced composite in aerospace applications: opportunities, challenges, and future perspective. Advanced Composites in Aerospace Engineering Applications, 471-498.
5. Bharath, K. N., P, M., Mavinkere Rangappa, S., Siengchin, S., Alexey, K., & Gorbatyuk, S. (2022). Waste coconut leaf sheath as reinforcement composite material with phenol-formaldehyde matrix. Polymer Composites, 43(4), 1985-1995.
6. Boyer, R. R., Cotton, J. D., Mohaghegh, M., & Schafrik, R. E. (2015). Materials considerations for aerospace applications. MRS Bulletin, 40(12), 1055–1066.
7. Bristow, J. W., & Irving, P. E. (2007). Safety factors in civil aircraft design requirements. Engineering Failure Analysis, 14(3), 459-470.
8. Campbell Jr, F. C. (2011). Manufacturing technology for aerospace structural materials. Elsevier.
9. Conroy, A., Halliwell, S., & Reynolds, T. (2006). Composite recycling in the construction industry. Composites Part A: Applied Science and Manufacturing, 37(8), 1216-1222.
10. Cunliffe, A. M., Jones, N., & Williams, P. T. (2003). Recycling of fibre-reinforced polymeric waste by pyrolysis: thermo-gravimetric and bench-scale investigations. Journal of analytical and applied pyrolysis, 70(2), 315-338.
11. Das, S. K., & Kaufman, J. G. (2008). Recycling aluminum aerospace alloys. Advanced Materials and Processes, 166(3), 34.
12. Das, S. K., Green, J. A. S., & Kaufman, J. G. (2010a). Aluminum recycling: Economic and environmental benefits. Light Metal Age, 68(1), 42.
13. Das, S. K., Green, J. A., Kaufman, J. G., Emadi, D., & Mahfoud, M. (2010b). Aluminum recycling—An integrated, industrywide approach. JOM, 62, 23-26.
14. Davis, J. R. (1993). Aluminum and aluminum alloys. ASM international.
15. [15] Dursun, T., & Soutis, C. (2014). Recent developments in advanced aircraft aluminium alloys. Materials & Design (1980-2015), 56, 862-871.
16. Eckelman, M. J., Ciacci, L., Kavlak, G., Nuss, P., Reck, B. K., & Graedel, T. E. (2014). Life cycle carbon benefits of aerospace alloy recycling. Journal of Cleaner Production, 80, 38-45.
17. Farinha, C. B., de Brito, J., & Veiga, R. (2019). Assessment of glass fibre reinforced polymer waste reuse as filler in mortars. Journal of Cleaner Production, 210, 1579-1594.
18. Ferdous, W., Manalo, A., Peauril, J., Salih, C., Reddy, K. R., Yu, P., ... & Heyer, T. (2020). Testing and modelling the fatigue behaviour of GFRP composites–Effect of stress level, stress concentration and frequency. Engineering Science and Technology, an International Journal, 23(5), 1223-1232.
19. Geier, N., Davim, J. P., & Szalay, T. (2019). Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: A review. Composites Part A: Applied Science and Manufacturing, 125, 105552.
20. Gutiérrez, E., & Bono, F. (2013). Review of industrial manufacturing capacity for fibre-reinforced polymers as prospective structural components in Shipping Containers. JRC Scientific and Policy Reports, JRC77823.
21. Hegde, S., Shenoy, B. S., & Chethan, K. N. (2019). Review on carbon fibre reinforced polymer (CFRP) and their mechanical performance. Materials Today: Proceedings, 19, 658-662.
22. Heinz, A., Haszler, A., Keidel, C., Moldenhauer, S., Benedictus, R., & Miller, W. S. (2000). Recent development in aluminium alloys for aerospace applications. Materials Science and Engineering: A, 280(1), 102-107.
23. Howe, S., Kolios, A. J., & Brennan, F. P. (2013). Environmental life cycle assessment of commercial passenger jet airliners. Transportation Research Part D: Transport and Environment, 19, 34-41.
24. Huda, Z., & Edi, P. (2013). Materials selection in design of structures and engines of supersonic aircrafts: A review. Materials & Design (1980-2015), 46, 552-560.
25. Hunter, T. (2009). A recycler's perspective on recycling carbon fibre pre-preg production scrap. In Carbon fibre recycling and reuse 2009 conference, IntertechPira, Hamburg, Germany.
26. Jiang, G., Pickering, S. J., Lester, E. H., Turner, T. A., Wong, K. H., & Warrior, N. A. (2009). Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol. Composites Science and Technology, 69(2), 192-198.
27. Joshi, M., & Chatterjee, U. (2016). Polymer nanocomposite: an advanced material for aerospace applications. In Advanced composite materials for aerospace engineering (pp. 241-264). Woodhead Publishing.
28. Karabin, M. E., Barlat, F., & Shuey, R. T. (2009). Finite element modeling of plane strain toughness for 7085 aluminum alloy. Metallurgical and Materials Transactions A, 40, 354-364.
29. Karuppannan Gopalraj, S., & Kärki, T. (2020). A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: Fibre recovery, properties and life-cycle analysis. SN Applied Sciences, 2(3), 433.
30. Kizaki, T., Zhang, J., Yao, Q., & Yanagimoto, J. (2020). Continuous manufacturing of CFRP sheets by rolling for rapid fabrication of long CFRP products. Composites Part B: Engineering, 189, 107896.
31. Krauklis, A. E., Karl, C. W., Gagani, A. I., & Jørgensen, J. K. (2021). Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. Journal of Composites Science, 5(1), 28.
32. Kumar, Y. K., & Lohchab, D. S. (2016). Influence of aviation fuel on mechanical properties of glass fibre-reinforced plastic composite. Chennai: IARJSET, 3(4), 58-66.
33. Li, S. S., Yue, X., Li, Q. Y., Peng, H. L., Dong, B. X., Liu, T. S., ... & Jiang, Q. C. (2023). Development and applications of aluminum alloys for aerospace industry. Journal of Materials Research and Technology.
34. M'Saoubi, R., Axinte, D., Soo, S. L., Nobel, C., Attia, H., Kappmeyer, G., ... & Sim, W. M. (2015). High performance cutting of advanced aerospace alloys and composite materials. CIRP Annals, 64(2), 557-580.
35. Marsh, G. (2008). Reclaiming value from post-use carbon composite. Reinforced Plastics, 52(7), 36-39.
36. Marsh, G. (2009). Carbon recycling: a soluble problem. Reinforced Plastics, 53(4), 22-27.
37. Mashhadi, H. A., Moloodi, A., Golestanipour, M., & Karimi,

E. Z. V. (2009). Recycling of aluminium alloy turning scrap via cold pressing and melting with salt flux. Journal of Materials Processing Technology, 209(7), 3138-3142.

38. Masuelli, M. A. (2013). Introduction of fibre-reinforced polymers− polymers and composites: concepts, properties and processes. In Fibre reinforced polymers-the technology applied for concrete repair. IntechOpen.
39. Mattsson, C., André, A., Juntikka, M., Tränkle, T., & Sott, R. (2020, October). Chemical recycling of End-of-Life wind turbine blades by solvolysis/HTL. In IOP conference series: materials science and engineering (Vol. 942, No. 1, p. 012013). IOP Publishing.
40. Mehdikhani, M., Gorbatikh, L., Verpoest, I., & Lomov, S. V. (2019). Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. Journal of Composite Materials, 53(12), 1579-1669.
41. Meyer, L. O., Schulte, K., & Grove-Nielsen, E. (2009). CFRP-recycling following a pyrolysis route: process optimization and potentials. Journal of composite materials, 43(9), 1121-1132.
42. Morampudi, P., Namala, K. K., Gajjela, Y. K., Barath, M., & Prudhvi, G. (2021). Review on glass fibre reinforced polymer composites. Materials Today: Proceedings, 43, 314-319.
43. Muhammad, A., Rahman, M. R., Baini, R., & Bakri, M. K. B. (2021). Applications of sustainable polymer composites in automobile and aerospace industry. In Advances in sustainable polymer composites (pp. 185-207). Woodhead Publishing.
44. Nagaraju, S. B., Priya, H. C., Girijappa, Y. G. T., & Puttegowda, M. (2023). Lightweight and sustainable materials for aerospace applications. Lightweight and Sustainable Composite Materials (pp. 157-178). Woodhead Publishing.
45. Nakagawa, M., Shibata, K., & Kuriya, H. (2009, May). Characterization of CFRP using recovered carbon fibers from waste CFRP. In Second International symposium on fiber recycling, the fiber recycling.
46. Naqvi, S. R., Prabhakara, H. M., Bramer, E. A., Dierkes, W., Akkerman, R., & Brem, G. (2018). A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. Resources, conservation and recycling, 136, 118-129.
47. Nightingale, A. (2009). A guide to systematic literature reviews. Surgery (Oxford), 27(9), 381-384.
48. Nwankwo, C. O., Mahachi, J., Olukanni, D. O., & Musonda, I. (2023). Natural fibres and biopolymers in FRP composites for strengthening concrete structures: A mixed review. Construction and Building Materials, 363, 129661.
49. Ohtaki, M., Arakawa, T., & Murata, F. (2000). A new proposal of continuous agitation vacuum distillation process (CAVP) to remove Zn from aluminum scrap melt. Recycling of Metals and Engineered Materials, 993-1003.
50. Oliveux, G., Bailleul, J. L., La Salle, E. L. G., Lefèvre, N., & Biotteau, G. (2013). Recycling of glass fibre reinforced composites using subcritical hydrolysis: reaction mechanisms and kinetics, influence of the chemical structure of the resin. Polymer degradation and stability, 98(3), 785-800.
51. Oliveux, G., Dandy, L. O., & Leeke, G. A. (2015). Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. Progress in Materials Science, 72, 61-99.
52. Oliveux, G., Le Gal La Salle, E., & Bailleul, J. L. (2011, January). Recycling by solvolysis thermosetting composite materials of sustainable surface transport. In AIP conference proceedings (Vol. 1315, No. 1, pp. 209-214). American Institute of Physics.
53. Paraskevas, D., Kellens, K., Dewulf, W., & Duflou, J. R. (2015). Environmental modelling of aluminium recycling: a Life Cycle Assessment tool for sustainable metal management. Journal of Cleaner Production, 105, 357-370.
54. Pickering, S. J. (2006a). Recycling technologies for thermoset composite materials—current status. Composites Part A: applied science and manufacturing, 37(8), 1206-1215.
55. Pickering, S. J., Kelly, R. M., Kennerley, J. R., Rudd, C. D., & Fenwick, N. J. (2000). A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. Composites science and technology, 60(4), 509-523.
56. Pickering, S. J., Turner, T. A., & Warrior, N. A. (2006b, November). Moulding compound development using recycled carbon fibres. In Proceedings of the 38th SAMPE fall technical conference: global advances in materials and process engineering (pp. 6-9).
57. Pimenta, S., & Pinho, S. T. (2011). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. Waste management, 31(2), 378-392.
58. Rajak, D. K., Wagh, P. H., & Linul, E. (2021). Manufacturing technologies of carbon/glass fibre-reinforced polymer composites and their properties: A review. Polymers, 13(21), 3721.
59. Rambabu, P. P. N. K. V., Eswara Prasad, N., Kutumbarao, V. V., & Wanhill, R. J. H. (2017). Aluminium alloys for aerospace applications. Aerospace materials and material technologies: volume 1: aerospace materials, 29-52.
60. Ramli, N., Norkhairunnisa, M., Ando, Y., Abdan, K., & Leman, Z. (2022). Advanced polymer composite for aerospace engineering applications. In Advanced Composites in Aerospace Engineering Applications (pp. 1-21). Cham: Springer International Publishing.
61. Rani, M., Choudhary, P., Krishnan, V., & Zafar, S. (2021). A review on recycling and reuse methods for carbon fibre/glass fibre composites waste from wind turbine blades. Composites part B: engineering, 215, 108768.
62. Rioja, R. J., & Liu, J. (2012). The evolution of Al-Li base products for aerospace and space applications. Metallurgical and Materials Transactions A, 43(9), 3325-3337.
63. Sathishkumar, T. P., Satheeshkumar, S., & Naveen, J. (2014). Glass fibre-reinforced polymer composites–a review. Journal of reinforced plastics and composites, 33(13), 1258-1275.
64. Scaffaro, R., Di Bartolo, A., & Dintcheva, N. T. (2021). Matrix and filler recycling of carbon and glass fibre-reinforced polymer composites: A review. Polymers, 13(21), 3817.
65. Shivanagere, A., Sharma, S., & Goyal, P. (2018). Modelling of glass fibre reinforced polymer (Gfrp) for aerospace applications. Journal of Engineering Science and Technology, 13(11), 3710-3728.
66. Singh, P., Pungotra, H., & Kalsi, N. S. (2017). On the characteristics of titanium alloys for the aircraft applications. Materials today: proceedings, 4(8), 8971-8982.
67. Soo, V. K., Peeters, J., Paraskevas, D., Compston, P., Doolan, M., & Duflou, J. R. (2018). Sustainable aluminium recycling of end-of-life products: A joining techniques perspective. Journal of Cleaner Production, 178, 119-132.
68. Soutis, C. (2005). Fibre reinforced composites in aircraft construction. Progress in aerospace sciences, 41(2), 143-151.
69. Starke Jr, E. A., & Staley, J. T. (1996). Application of modern aluminum alloys to aircraft. Progress in aerospace sciences, 32(2-3), 131-172.
70. Starke Jr, E. A., & Staley, J. T. (1996). Application of modern aluminum alloys to aircraft. Progress in aerospace sciences, 32(2-3), 131-172.
71. Tao, Y., Hadigheh, S. A., & Wei, Y. (2023, July). Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: A critical review and cost benefit analysis. In Structures (Vol. 53, pp. 1540-1556). Elsevier.
72. Tong, L., Mouritz, A. P., & Bannister, M. K. (2002). 3D fibre

reinforced polymer composites. Elsevier.
73. Van den Eynde, S., Bracquené, E., Diaz-Romero, D., Zaplana, I., Engelen, B., Duflou, J. R., & Peeters, J. R. (2022). Forecasting global aluminium flows to demonstrate the need for improved sorting and recycling methods. Waste Management, 137, 231-240.
74. Vermeulen, B., & Van Tooren, M. J. L. (2006). Design case study for a comparative performance analysis of aerospace materials. Materials & design, 27(1), 10-20.
75. Vieira, D. R., Vieira, R. K., & Chang Chain, M. (2017). Strategy and management for the recycling of carbon fibre-reinforced polymers (CFRPs) in the aircraft industry: a critical review. International Journal of Sustainable Development & World Ecology, 24(3), 214-223.
76. Wanhill, R. J. H. (1994). Flight simulation fatigue crack growth testing of aluminium alloys: specific issues and guidelines. International journal of fatigue, 16(2), 99-110.
77. Witik, R. A., Gaille, F., Teuscher, R., Ringwald, H., Michaud, V., & Månson, J. A. E. (2012). Economic and environmental assessment of alternative production methods for composite aircraft components. Journal of Cleaner Production, 29, 91-102.
78. Yazdanbakhsh, A., Bank, L. C., Rieder, K. A., Tian, Y., & Chen, C. (2018). Concrete with discrete slender elements from mechanically recycled wind turbine blades. Resources, Conservation and Recycling, 128, 11-21.
79. Zhang, J., Song, B., Wei, Q., Bourell, D., & Shi, Y. (2019). A review of selective laser melting of aluminum alloys: Processing, microstructure, property and developing trends. Journal of Materials Science & Technology, 35(2), 270-284.
80. Zhang, W., & Xu, J. (2022). Advanced lightweight materials for Automobiles: A review. Materials & Design, 221, 110994.
81. Zhang, X., Chen, Y., & Hu, J. (2018). Recent advances in the development of aerospace materials. Progress in Aerospace Sciences, 97, 22-34.
82. Zhou, B., Zhang, M., Wang, L., & Ma, G. (2021). Experimental study on mechanical property and microstructure of cement mortar reinforced with elaborately recycled GFRP fiber. Cement and Concrete Composites, 117, 103908.
83. Zhu, L., Li, N., & Childs, P. R. N. (2018). Light-weighting in aerospace component and system design. Propulsion and Power Research, 7(2), 103-119.